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Characterization of a Low-phase-noise, High-power (370 mW), External-cavity Semiconductor Laser

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CHARACTERIZATION OF A LOW-PHASE-NOISE, HIGH-POWER (370 mW), EXTERNAL-CAVITY SEMICONDUCTOR LASER

ABSTRACT

Past research efforts have attempted to demonstrate semiconductor lasers with reduced levels of phase noise, approaching noise levels typically observed in highly coherent solid state lasers. In this work, detailed phase noise measurements have been performed on an expanded-mode, external cavity semiconductor laser with a longer cavity length and much higher output power than similar commercial lasers. These results demonstrate that the high frequency phase noise due to spontaneous emission was reduced significantly relative to existing COTS semiconductor lasers. The measured phase noise for this novel external cavity semiconductor laser was within a factor of two of commercially available fiber lasers, and within a factor of 20 of a Nd:YAG laser, over the 1 Hz to 10 MHz frequency range.

INTRODUCTION

High-power, highly-coherent laser sources are critical to a wide range of military, commercial, and scientific sensing applications. These applications include fiber optic sensing, microwave photonics, LIDAR, and gravity wave detection. For many of these applications the magnitude of the low-frequency phase noise (or frequency jitter) is a critical consideration, in addition to price, output power, and size. Semiconductor lasers have many potential benefits over solid state lasers, including their low-cost, compact size, capability of direct frequency modulation using current injection, and the potential for device integration. Unfortunately, their phase noise is typically larger than in solid state lasers, though both types of lasers suffer from $1/f$ noise at frequencies near the acoustic band (20 Hz to 20 kHz). However, recent work has shown that the phase noise of relatively inexpensive external cavity semiconductor lasers (ECSLs) has steadily been reduced [1, 2]. Over the acoustic frequency band, the phase noise for the best COTS ECSLs is within reach of highly-coherent solid state lasers such as a Nd:YAG laser, and almost equal to that of Er-doped fiber lasers. Unfortunately, the white noise due to spontaneous emission still dominates for ECSLs at frequencies above the acoustic band (between 10 kHz and 10 MHz). The effort reported here seeks the reduction of the white noise component commonly observed in ECSLs. Reducing the phase noise in this high-frequency band is important since it can alias to lower frequencies with some demodulation schemes [3], and affect the sensor detection threshold.

In this work we characterize the phase noise of a high-power, expanded transverse-mode ECSL, or slab coupled optical waveguide external cavity laser (SCOWECL), designed and built by MIT Lincoln Laboratory [4-6]. As shown in Fig. 1(a), the SCOWECL has a unique epitaxial layer design with an underlying passive waveguide below the active quantum well region. In addition, it has a longer cavity length and higher output power relative to other ECSLs tested previously [1, 2, 7]. In accordance with the theory discussed below, the white noise due to spontaneous emission has been reduced significantly in the SCOWECL. The SCOWECL has a peak output power 370 mW for 4 A of applied current bias. Such high output powers make this laser useful for a variety of sensing applications, especially in situations where a single laser source can be used to illuminate multiple sensors in an array or for sensor systems limited by detector shot noise. This work demonstrates that the high-frequency phase noise of ECSLs is amenable to reduction. Discussion of other sources of phase noise (e.g., $1/f$ noise) that can be ameliorated will be discussed in Appendix C since there is considerable promise for future reductions in lasers utilizing more optimized designs and fabrication methods.

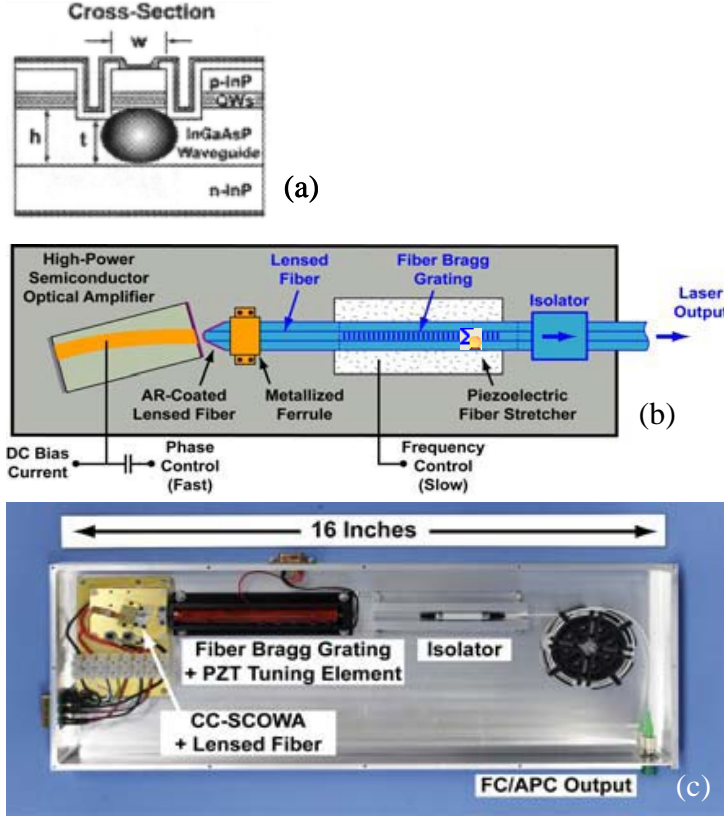


Figure 1. Illustrations and photograph of the MIT-Lincoln Laboratories 1.55 micron slab-coupled optical waveguide external cavity laser (SCOWECL): (a) Schematic of the expanded-mode waveguide design (b) Schematic of the external cavity design (c) photograph of a packaged SCOWECL device. Reprinted from Juodawlkis et al. [5, 6].

THEORETICAL BACKGROUND

In order to fabricate highly-coherent semiconductor lasers, it is important to understand the fundamental origins of their phase noise. Previous work has shown that the power spectrum of the phase noise $S_\phi(f)$ [or frequency noise $S_v(f)$] for semiconductor lasers has two components, a frequency independent component C due to spontaneous emission and a component K due to $1/f$ noise [1, 2, 8]:

$$S_\phi(f) = C / P + K / f, \quad (1)$$

where P is the optical power. Unfortunately, the precise origin of the $1/f$ noise is not well understood theoretically. However there are several documented sources such as fluctuations from leakage currents within the buried heterostructure device, carrier traps caused by dangling bonds at the cleaved laser facets, and mode competition noise [9-12]. Despite this uncertainty, the magnitude of the $1/f$ noise in commercially available semiconductor lasers has decreased dramatically over the years with the introduction of ECSLs that have been optimized for lower chirp and reduced leakage current [1, 2].

From a theoretical perspective, the linewidth broadening, or frequency noise, due to spontaneous emission is better understood than the $1/f$ noise. A detailed calculation for the magnitude of the linewidth broadening in a semiconductor laser diode due to spontaneous emission is given by the modified Schawlow-Townes equation (as derived by C. H. Henry [13-17]). It has been shown that the linewidth of a semiconductor laser can be written as,

$$\Delta\nu \sim S_\nu(\text{white}) \sim \frac{\Delta\nu_{\text{ST}}(1+\alpha^2)\xi^2}{F^2} \sim \frac{(1+\alpha^2)\xi^2}{L^2PF^2}, \quad (2)$$

where α is the linewidth enhancement factor (LEF), P is the laser output power, L is the cavity length, and $\Delta\nu_{\text{ST}}$ is the Schawlow-Townes linewidth applicable to gas and solid state lasers. The original relationship was later generalized to include an external cavity and passive segments of the optical cavity, where ξ is the fraction of the laser cavity occupied by a passive section, and F is the linewidth reduction factor taking into account the effects of detuned loading and blue detuning [13, 16, 17]. From this relation it is clear that in order to reduce the contribution of the phase noise from spontaneous emission, the cavity length L , the optical power P , and F should be increased, whereas the chirp parameter α and the ξ factor need to be decreased. In accordance with Eq. (2), the magnitude of the white phase noise due to spontaneous emission for the SCOWECL should be smaller than in the COTS ECSLs measured previously since the SCOWECL has a higher output power and a longer cavity length.

Although the laser linewidth is traditionally used to characterize the degree of coherence in a variety of lasers, phase noise measurement data is far more useful in determining the impact of noise on sensor performance. The laser linewidth and phase noise [or frequency noise $S_\nu(f)$] are closely related [14, 18]: The linewidth is the integral of the frequency noise over all frequencies [19]. As a consequence, a linewidth measurement results in a *single* number that does not capture the strong frequency dependence of the phase noise described by Eq. (1), the magnitude of which is often critical in evaluating laser-limited noise floors of many sensing systems. In the limit the phase noise is purely white [i.e., no frequency dependence $S_\nu(0)$], it can be shown that $\Delta\nu = 2\pi S_\nu(0)$ [20]. This simple correspondence can be used to relate phase noise and linewidth measurements in the limit of zero $1/f$ noise, or conversely for linewidth measurements with short integration times that miss the low-frequency noise contribution. As shown below, mechanical resonances (from stray acoustic pickup and background room vibration) and current supply noise were clearly visible in phase noise measurements, yet were obscured in linewidth measurements [5]. For this reason, careful measurements of the laser phase noise have been performed in this work in lieu of measurements of the laser linewidth.

(a) Fiber Optic Interferometer

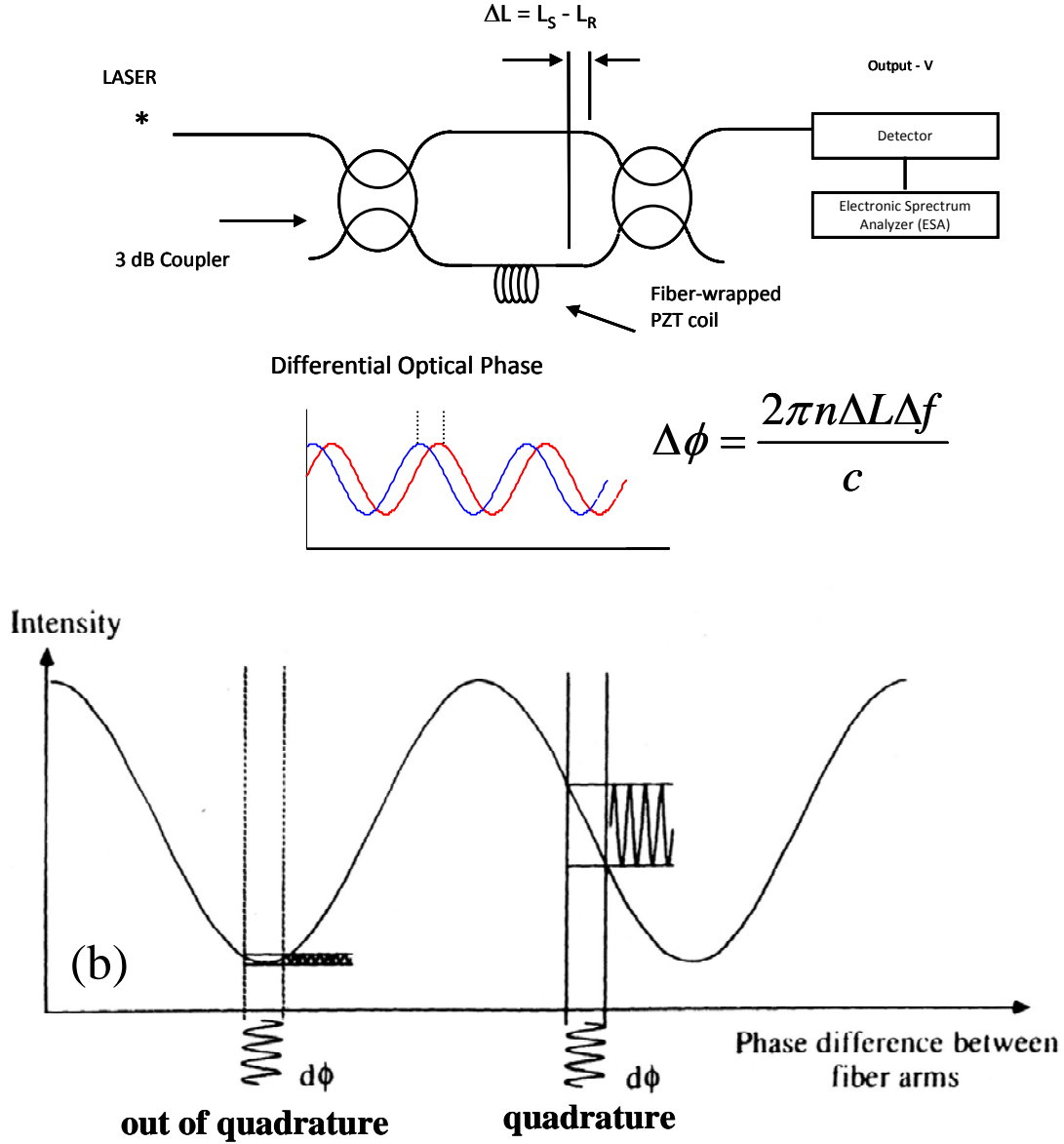


Figure 2. (a) Schematic of the experimental setup used to measure the phase noise across a path-imbalanced Mach-Zehnder Interferometer (MZI) with a fiber-wrapped PZT. (b) The optical intensity profile of a MZI as a function of the phase difference between the two arms of the interferometer. In response to a sinusoidal phase modulation ($\Delta\phi$) of the PZT, the MZI transfer function is large in quadrature and much smaller at the MZI minimum, or out of quadrature point. Taken from [21].

PHASE NOISE OF THE SCOWECL VS COTS ECSLS AND SOLID STATE LASERS

The phase noise measurement technique used here was similar to previous work [1, 2, 22], see Appendix A for details. An all fiber-optic path imbalanced Mach-Zehnder interferometer (PI-MZI), illustrated schematically in Fig. 2(a), was used to measure the laser phase noise. A MZI held in quadrature converts the laser phase noise (or frequency jitter) to an intensity noise [see Fig. 2(b)]. The MZI was housed in a thick-walled (0.25 in) metal box lined with a heavy, sound-absorbing, lead-foam composite to help provide isolation from acoustic pickup and thermal drifts. In order to control the phase of the MZI, one arm of the interferometer included a cylindrical PZT [Vernitron, lead zirconate titanate-PZT4] with approximately 5 m of fiber wrapped on it. The MZI was held in quadrature by using either a dc voltage supply and adjusting the voltage to the PZT manually as the phase drifted, or by using a low bandwidth active servo feedback circuit to the PZT. The output of the MZI was coupled to a detector, which converts the intensity noise to a voltage noise as recorded by an HP electronic spectrum analyzer (ESA). As shown in Appendix A, one then needs to determine a calibration constant that converts the measured voltage noise signal, in units of $\text{dB } V_{\text{rms}}/\text{rt}(\text{Hz})$, to laser phase noise in units of $\text{dB rad}_{\text{rms}}/\text{rt}(\text{Hz})$.

A series of phase noise measurements were performed using the SCOWECL as the source for different current biases [from 1.2 A to 3 Amps] and heat sink temperatures [ranging from 16 C to 24 C]. Since the SCOWECL needed relatively large current biases, electronic noise from a commercial current supply was an issue. Accordingly, a high current rating 12 V battery supply, utilizing high power resistors and a rheostat to control the laser current bias, was constructed in order to reduce the current supply noise (see Appendix B for details). The lowest phase noise data for the MIT-LL SCOWECL was obtained using the battery-based current supply (see green data trace in Fig. 3). For comparison purposes, phase noise data shown previously [2] for a Nd:YAG laser, a COTS ECSL, and a fiber laser are replotted in Figs. 3(a) and 3(b). Currently, the Nd:YAG represents the laser phase noise “gold standard” as the lowest noise source combined with the highest output power (around 200 mW). For the results shown in Fig. 3, the *amplitude* of the phase noise, or the square root of the noise power, $S_{\phi}^{1/2}(f)$, was plotted. Note the $1/f$ noise dependence is actually a $1/f^{1/2}$ dependence, with the value of the exponent (1/2) being approximate. Since $\Delta\phi=2\pi n_{\text{eff}}\Delta L\Delta f/c$ for a 1 m path imbalance in silica, the correspondence between the two y-axes in Fig. 3 is given by $S_v^{1/2}(f)=32.7S_{\phi}^{1/2}(f)$.

There are several common features of this phase noise data. All of the lasers exhibit a $1/f$ -like noise dependence over some frequency range. In Fig. 3(a), the phase noise data for the Emcore [K2] laser transitions from a $1/f$ noise dependence to a flat white noise due to spontaneous emission [see Eq. (1)]. In contrast, the phase noise for the SCOWECL in Fig. 3 has a $1/f$ -like dependence over the *entire* measurement frequency range [1 Hz to 10 MHz]. The white noise for the SCOWECL was smaller than the $1/f$ noise out to 10 MHz and was not observed. The elimination of this high-frequency white-noise component for the SCOWECL, relative to COTS ECSLS, represents a significant reduction of the phase noise for a semiconductor laser. This dramatic improvement was achieved by reducing the magnitude of the white noise in the SCOWECL along the lines of the theory [Eq. (2)]. Though an exact quantitative comparison is currently lacking, this was presumably achieved through the use of longer cavities, higher output powers, and a smaller ξ factor. In summary, the phase noise for the SCOWECL was within a factor of two of a fiber laser, and within a factor of 20 or so of a Nd:YAG laser over a broad range of frequencies from 1 Hz to 10 MHz [see Fig. 3(b)].

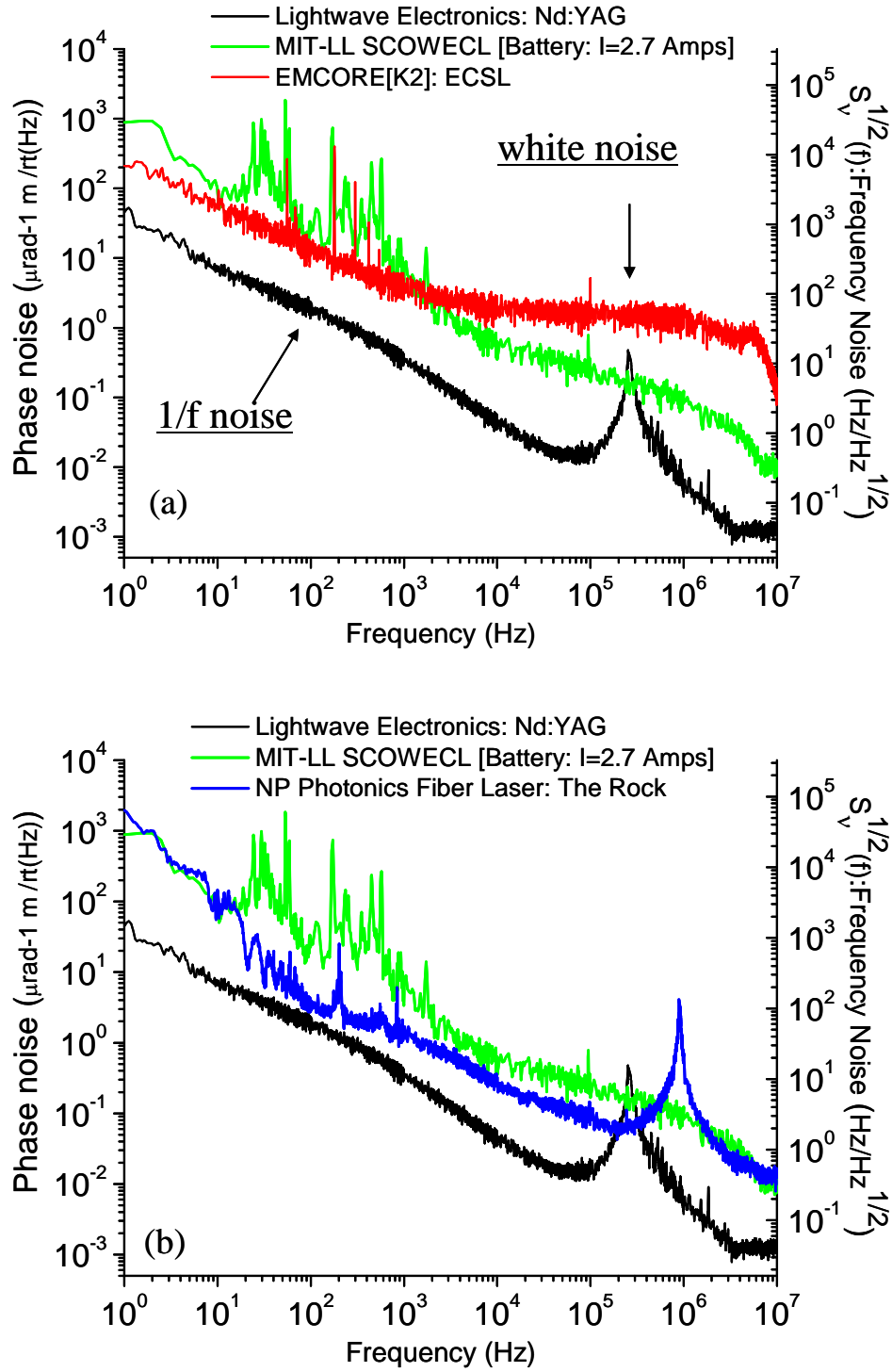


Figure 3. Comparison of the phase noise performance of the MIT-LL SCOWECL relative to a commercial ECSL and solid state lasers, namely a Nd:YAG and a fiber laser. The phase noise of the SCOWECL is shown in green in both figures. In (a) the phase noise of the SCOWECL is compared to a smaller, lower power, ECSL, where in (b) it is compared to a commercial fiber laser. The phase noise for the Nd:YAG is used as a baseline comparison in both plots.

There are several anomalous features of the phase noise data shown in Fig. 3. It can be seen that at low frequencies (20 Hz to 7 kHz), the phase noise data for the SCOWECL exhibits a broad series of resonances from room vibration and acoustic pickup. This is due to the fact the prototype SCOWECL shown in Fig. 1(c) was not packaged to minimize acoustic coupling, however this packaging issue can be readily addressed in future devices. Note that the well-packaged commercial ECSL from Emcore [K2] did not show evidence of acoustic pickup. Nor was there electronic noise (except for a tonal at 60 Hz, and harmonics thereof) for the Emcore [K2] laser since the battery-based commercial ILX Lightwave LDX-3620 was used to provide the dc current bias. The RIN peaks for the Nd:YAG and the fiber laser are clearly visible at 300 kHz and 900 kHz respectively. The RIN peak was visible since the phase noise decreases inversely with frequency to the point that it was equal to the intensity noise, even for an 82 m path imbalance. Above 3 MHz, for the Nd:YAG, the fiber laser, and the SCOWECL, the phase noise was actually consistent with the measurement system noise floor due to either detector noise or the noise floor of the electronic spectrum analyzer.

As mentioned above, electronic noise from a commercial current supply contributed greatly to the phase noise, necessitating the use of a battery-based current supply. In Fig. 4(a) the impact of current supply noise is clearly visible upon inspection of the orange and blue curves. For these measurements, an ILX Lightwave LDC-3900 mainframe with an LCM-39440 Current Source TE Controller was used. The current bias settings were 1.2 A and 1.9 A, out of a 2 A maximum, with a TEC temperature of 16 C. A large “bump” in the phase noise, centered at 40 kHz, was observed at 1.2 A, and expanded in size for the 1.9 A current bias. However, there was no corresponding “bump” in the phase noise for the battery source operating at 2.7 A as shown by the green curve reproduced from Fig. 3. In fact, as shown in Fig. 4(b), the phase noise was independent of the current bias over the range 1.1 A to 2.3 A. The magnitude of the electronic noise contribution to the phase noise was less prominent for the commercial current modules with higher maximum current ratings relative to the applied bias. As the data in Fig. 4(b) demonstrates, the electronic noise contribution was smaller using a 4 Amp maximum ILX LCM-39400 Current Source TE Controller at a current bias of 1.9 A, half the maximum rating, relative to using the LCM-39440 module operated essentially at the maximum current rating of 2 A. It is apparent that with the proper design, the contribution of electronic noise to the phase noise from commercial current supplies can be reduced.

CONCLUSIONS

In conclusion, this work demonstrates that the phase noise of ECSLs can be greatly improved by proper design. By designing a high-power ECSL, with relatively long cavity lengths, the white phase noise contribution from spontaneous emission was reduced significantly such that it was smaller than the $1/f$ noise out to 10 MHz. This was in contrast to previous phase noise measurements on lower power ECSLs with much shorter external cavities that exhibited $1/f$ noise in the acoustic band and white noise at higher frequencies. The phase noise from 1 Hz to 10 MHz for this SCOWECL was within a factor of two on average of commercially available fiber lasers and within a factor of 20 of relatively expensive Nd:YAG lasers. Also, the output power of the SCOWECL was on the order of 300 mW, comparable to the maximum power of the Nd:YAG depending on the manufacturer and model number. Demonstrating such low phase noise performance with high output power in a semiconductor laser is potentially of great benefit to a variety of sensing systems due to their low cost, compact size, potential for direct frequency modulation using current injection, and amenability for device integration.

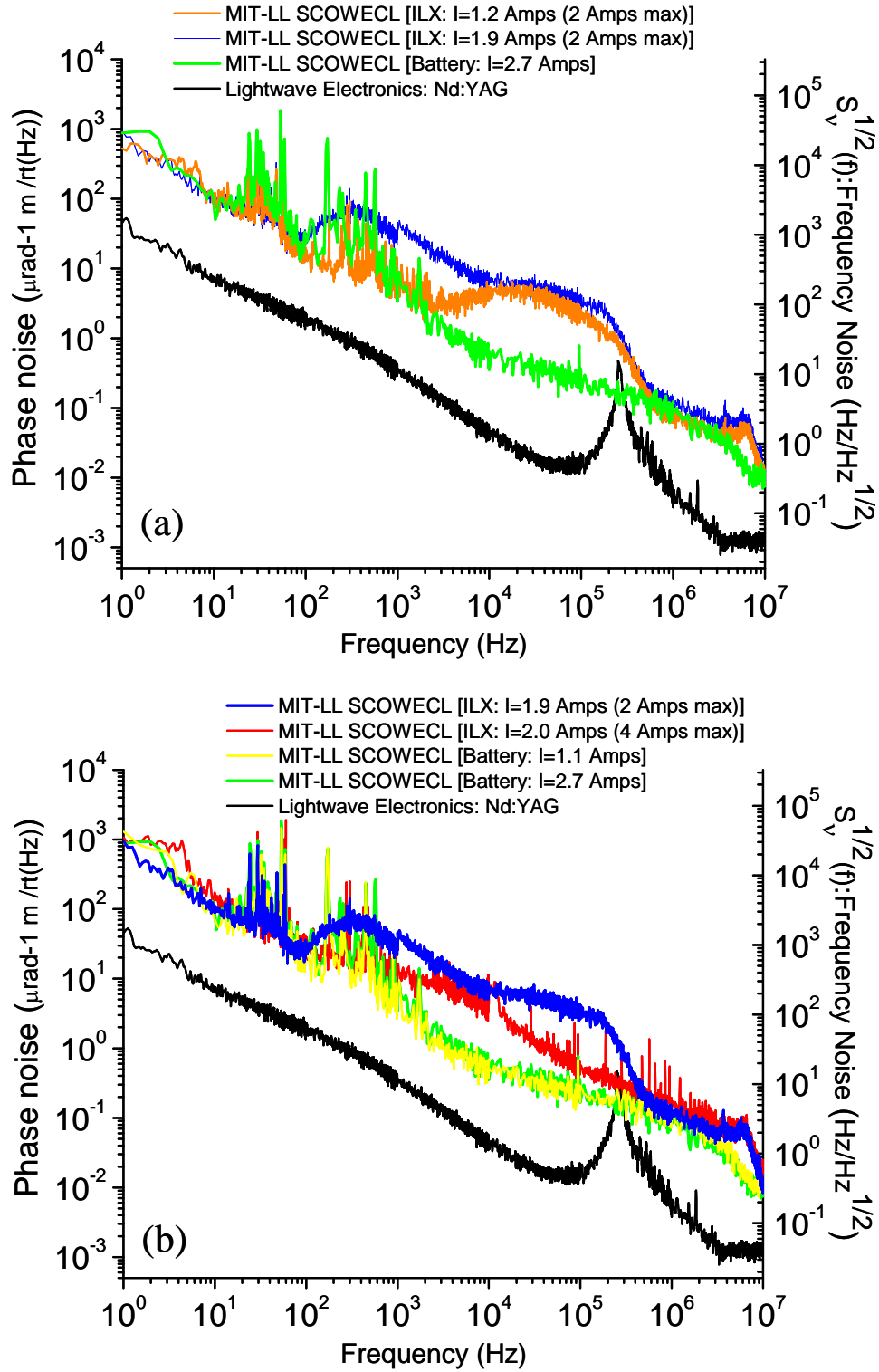


Figure 4. Phase noise data for the SCOWECL comparing the use of a commercial current supply with a 12 V battery-based supply at different bias currents. (a). Observation of increased phase noise as a function of current bias [1.2 A and 1.9 A] for the ILX Lightwave current supply, compared to the phase noise for a battery source at 2.3 A. (b) The phase noise data for different bias currents for the battery source [1.1 A and 2.3 A] and at about 2 A for the ILX source but using different modules with different maximum current ratings.

Appendix A

PHASE NOISE MEASUREMENT TECHNIQUE

A fiber-optic Mach-Zehnder Interferometer (MZI) with path imbalance ΔL was used to perform the phase noise measurements (see Fig. 2). The phase-difference of the MZI is quite sensitive to even small changes in the fiber effective index of refraction from temperature fluctuations or small strains due to background room vibration. This MZI was isolated from such environmental noise and thermal drift by placing it in a large vibration isolation box lined with lead foam composite [Soundcontrol Mat from Sound Control] (see Fig. B2). One output from the MZI was fed into an optical detector, and an electronic spectrum analyzer (ESA) was used to measure the voltage spectral density [in units of dB $V_{\text{rms}}/\text{rt}(\text{Hz})$]. The key aspect of the laser phase noise measurement was the accurate determination of the calibration constant, $C_{v\phi} = \Delta\phi/\Delta V$ [or $20\log(C_{v\phi})$ on a log scale], that converts the power spectral density (PSD) of the detector voltage to units of phase noise. An inline PZT on one arm of the interferometer was used to hold the interferometer in quadrature using feedback and to modulate the optical phase by a known amount to obtain $C_{v\phi}$.

The starting point to determine $C_{v\phi}$ is the following equation,

$$V = A + B\cos(\Delta\phi), \quad (\text{A.1})$$

which quantifies the magnitude of the detector voltage V as a function of the phase difference $\Delta\phi = 2\pi n_{\text{eff}}\Delta L/\lambda$ between the two arms of the MZI (see Fig. 2). In this expression n_{eff} is the effective index of the fiber ($n_{\text{eff}} = 1.46$ for silica), A is the optical intensity of one output in the absence of interference, and B the amplitude of the interference term. $C_{v\phi}$ can be readily determined using two different mathematical relationships. One method for determining $C_{v\phi}$ involves taking the derivative (or slope) of Eq. (A.1) evaluated at quadrature ($\Delta\phi = 0$):

$$\frac{\Delta V}{\Delta\phi} = \text{slope} = B\sin(\Delta\phi) \Big|_{\Delta\phi = \frac{\pi}{2}} = B = \frac{V_{\text{max}} - V_{\text{min}}}{2}, \quad (\text{A.2})$$

where the extremes of the voltage swings (V_{max} and V_{min}) are determined experimentally (see Fig. A1). The voltage-phase conversion factor is given by $C_{v\phi} = \Delta\phi/\Delta V = 1/B = 2/(V_{\text{max}} - V_{\text{min}})$ and has the units of radians per volt. Therefore, by measuring the voltage swings of the interferometer as it drifts between the condition of constructive and destructive interference (i.e., between V_{max} and V_{min}), the conversion factor between voltage noise and phase noise was readily determined. Since the PSD is recorded on a log scale, the scale factor $20\log(C_{v\phi}) = 20\log(\Delta\phi/\Delta V)$ was *added* to data from the ESA. One systematic approach was to have V_{max} and V_{min} fill up all 8 divisions on the oscilloscope. For a typical detector with a gain of 2000 V/W [for example, the OPTIPHASE V-600 Tunable Optical Converter], with 0.5 mWatts of incident optical power, the DC detector voltage was 1 V. For an oscilloscope setting of 0.2 V/Div, assuming a visibility near 0.7, the maximum excursion was 1.84 V [see Fig. A1(a)], with minimum of 0.31 V. Using these numbers, the voltage to phase calibration was given by $C_{v\phi} = 20\log(1.53/2) = 2.3 \text{ dB re-rad re-1 } V_{\text{rms}}$.

A second method for determining $C_{v\phi}$, centers on the application of a sinusoidal PZT voltage V_{PZT} , which yields the MZI response of the form

$$V = A + B\cos(\Delta\phi) = A + B\cos[D + E\sin(2\pi ft)]. \quad (\text{A.3})$$

Again we are calculating $20\log(C_{v\phi}) = 20\log(\Delta\phi/\Delta V)$, only this time by quantifying the phase change $\Delta\phi$ for a given modulation depth $E = \Delta V$. The interferometer output as viewed on the oscilloscope is now described by a

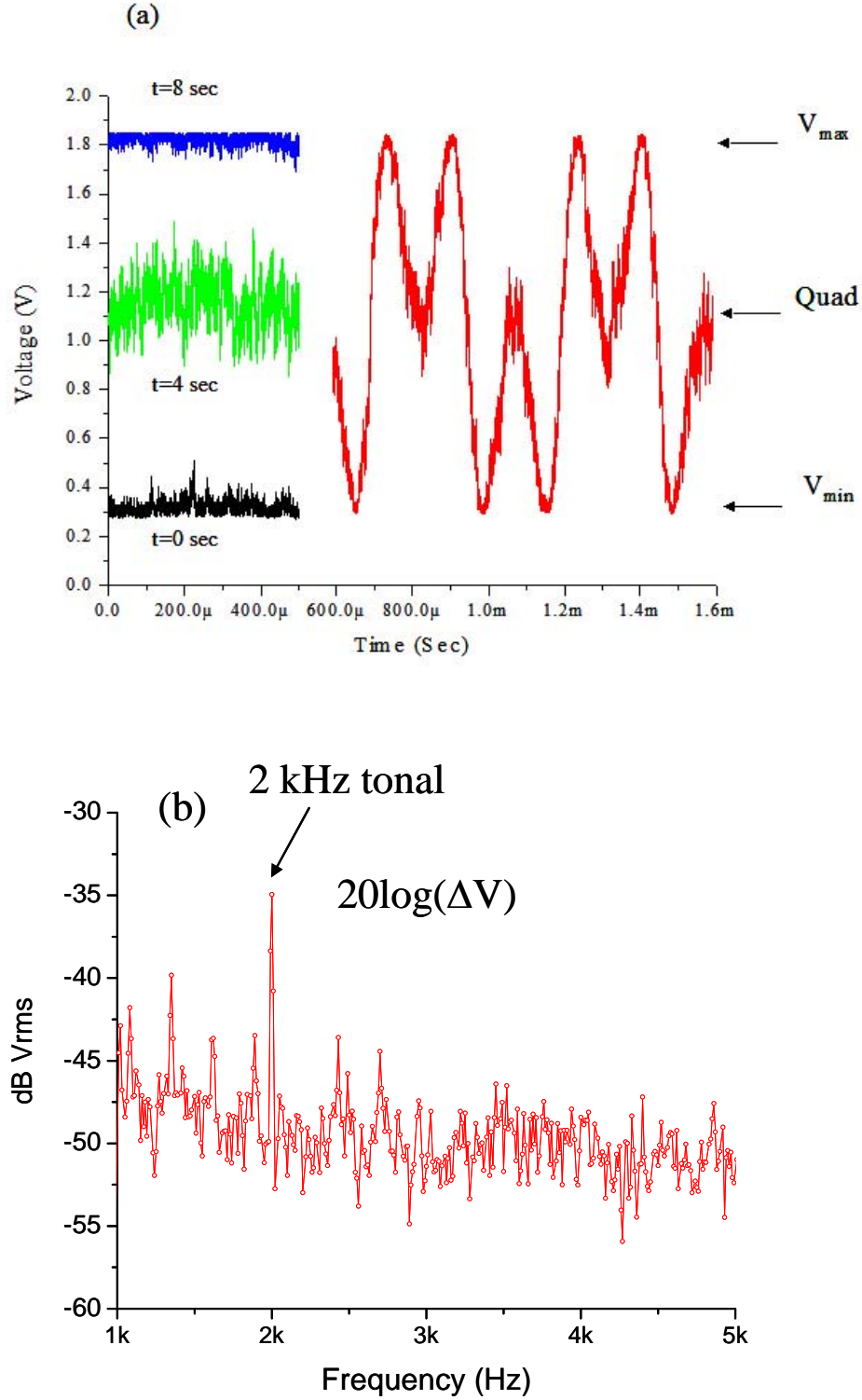


Figure A1. Oscilloscope traces and ESA data used in the course of a phase noise calibration measurement. (a) Interferometric signal viewed on an oscilloscope with no applied tonal at different points in time as the phase drifts in and out of quadrature (i.e., 2π radians). The characteristic Bessel pattern of the MZI where the PZT was driven sinusoidally. (b) Calibration tone data from the HP ESA used to determine $C_{v\phi}$.

modified Bessel function. This is illustrated by the measurement results shown on the right in Fig. A1(a), where the PZT drive voltage V_{PZT} was chosen to generate an $E=\pi_p$ shift in phase, thus generating one complete cycle of the modulation term E . The data shown in Fig. A1(a) was obtained for the case $D=0$, where the oscillation of V is symmetric about the quadrature point. The voltage applied to the PZT can then be reduced by a factor of 100 such that the phase change is in the small signal regime where $\sin(\Delta\phi) \sim \Delta\phi$. The induced phase change is given by $20\log(\Delta\phi) = 20\log[2\pi_p/(2\sqrt{2} \cdot 100)] = -33.1 \text{ dB re rad}_{\text{rms}}$, where the $2\sqrt{2}$ converts peak-to-peak to rms to match the voltage measurement response. **Make sure the VSA plots the power spectrum not PSD [i.e., units of $\text{dB } V_{\text{rms}}$ not $\text{dB } V_{\text{rms}}/\text{rt(Hz)}$] when obtaining the peak value $20\log(\Delta V) = -35 \text{ dB } V_{\text{rms}}$ [see Fig. A1(b)].** The calibration constant in dB was given by $20\log(\Delta\phi/\Delta V) = -33.1 - (-35.0) = 1.9 \text{ dB re-rad/Volt}$, consistent with the value obtain using Method 1. Note that the value of V_{PZT} needed to generate a π_p phase shift depends on the amount of fiber wrapped on the PZT, but does not enter into the calculation for $20\log(C_{v\phi})$. Note also that the form of the oscilloscope trace similar to Method 1 can be maintained and $C_{v\phi}$ is readily given by $20\log[2/(V_{\text{max}}-V_{\text{min}})]$ as before, thus serving as a consistency check.

Since the phase noise scales with the path imbalance ΔL , a common convention is to scale the data relative to a 1 m path imbalance. Working on a log scale, the path imbalance correction factor is $20\log_{10}(\Delta L/1.0 \text{ m})$, so for a 0.3 m path imbalance you would add 10.46 dB re 1 m to the PSD data where for a 82 m path imbalance you would subtract a factor of 38.3 dB re 1 m. Other scale factors include the conversion to μrad : $20\log(10^6 \mu\text{rad/rad}) = 120 \text{ dB re } 1 \mu\text{rad}$. To convert back to a linear scale of μrad , just raise the sum of the above numbers to the power of $10^{\# / 20}$, where $\# = \text{ESA data} + 1.93 + 120 - 38.3$ (for the 82 m path for example). A plot similar to Fig. 3 should be the result. The phase noise data can also be converted to units of frequency jitter $[\text{Hz}/\text{rt(Hz)}]$, by scaling by $S_v^{1/2}(f) = 32.7 S_\phi^{1/2}(f)$, as was done in this paper. **Note: When actually recording the phase noise data, use power spectral density (PSD) since the VSA will automatically correct for the signal bandwidth, and the data will be in units of $\text{dB } V_{\text{rms}}/\text{rt(Hz)}$.**

There are a few necessary steps and technical details to be aware of while performing a phase noise measurement. For fiber interferometers with a 50/50 light split in each arm, $A=B$ in Eq. (A.1), but that assumes the electric field vectors in each arm recombine in parallel. In general this is not the case, and B is proportional to $\cos(\eta)$ where η is the half angle between the output state of polarizations (SOP) [see [23] and references therein for a more detailed discussion of Eqs. A1 and A3]. By using a polarization controller at the input to the MZI, one can optimize $\cos(\eta)$ to be very close to one. In order to keep the input polarization constant in time [i.e., $\cos(\eta)$ near one], secure the input fiber leads to keep them from dangling and responding to room vibrations. In practice, the absolute values for V_{max} and V_{min} depend on the laser output power, detector gain factor, and the polarization visibility term [i.e., $\cos(\eta)$]. In the limit of perfect visibility, or complete destructive interference, $V_{\text{min}}=0$. The output polarization of the fiber should be adjusted to maximize $\cos(\eta)$, and minimize V_{min} to the extent possible. In practice however there will always be some offset [see Fig. A1(a)]. To maximize $\cos(\eta)$ (or the visibility), simply bend the input fiber to the detector so there is no light and note the detector voltage zero point. Then, after releasing the bent fiber, adjust the polarization controller until V_{min} approaches the detector zero point. A reasonable value for V_{min} is around 10 to 20% of V_{max} , but the exact fraction is not critical. In the end, the difference between V_{max} and V_{min} is all that matters. **Note that the power spectral density on the ESA must be recorded when the interferometer phase is in quadrature ($\Delta\phi=0$), i.e., the detector DC voltage has drifted halfway between V_{max} and V_{min} .**

It is also important not saturate the detector with too much light, i.e., operate it in the linear response regime. However, in order to minimize the effect of detector shot noise you want as much light as possible on the detector, so the proper balance must be struck. In order to prevent detector saturation, a fiber attenuator was used to reduce the light intensity into an optical detector (Optiphase Model V600) to approximately 0.5 mWatt, a factor of 2 below detector saturation. This light level was large enough that detector shot noise was minimized appropriately. It is critical that the phase noise exceed the intensity noise, the noise floor of the

spectrum analyzer, and detector noise. Since the magnitude of the phase noise scales with the path imbalance, relatively long path imbalances are used to ensure the laser phase noise is larger than the RIN or instrumental noise. For the lasers such as a Nd:YAG, a fiber laser, or a low noise ECSL, a path imbalance of 80 m should suffice. For a regular DFB laser, without an external cavity, the magnitude of the phase noise for an 80 m MZI is too large. For excessive path imbalances, it becomes difficult to lock the MZI in quadrature and a certain fraction of the noise lies outside the linear response regime. As a result, a shorter path imbalance of 10 m (or shorter) should be used.

There are a few other checks that need to be followed to obtain repeatable measurements. For one, check that the phase noise is indeed much larger than the intensity noise. One way of quickly doing this is to watch the magnitude of the PSD signal on the ESA as the MZI drifts in and out of quadrature. The PSD should be observed to be a maximum at the quadrature point, and much smaller (by at least 10 dB as a general rule of thumb) when the detector voltage has drifted to V_{\max} (the out of quadrature point) [see Figs. 2 and A1]. If there is very little change in the magnitude of the PSD as the phase drifts in and out of quadrature, then the phase noise is either dominated by intensity noise or is below the measurement noise floor. In this case, a MZI with a longer path imbalance ΔL must be used. Look for this effect over several different frequency ranges from 1 Hz and 10 MHz.

The calibration constant and the PSD data should be recorded in rapid succession, and checked again after the measurement, to ensure that V_{\max} and V_{\min} , or $C_{v\phi}$, have not changed. One easy technique is to make sure V_{\max} and V_{\min} still fill up 8 divisions on the oscilloscope, both before and after the PSD is recorded [see Fig. A1(a)]. If not, adjust the visibility using the polarization controller, and/or change the input power to the detector using the attenuator. If the laser, the MZI input fiber leads, and the MZI itself, are sufficiently isolated, the calibration constant should not change by more than a few percent over the course of several minutes. If the oscilloscope trace is oscillating rapidly [see Fig. A1(a)], it will be difficult to lock the MZI in quadrature. Slight temperature variations cause the MZI phase ($\Delta\phi$) to oscillate rapidly. It might be necessary to increase the degree of environmental isolation by placing BOTH the laser and the MZI in the isolation box, though for many lasers this is not possible. Packaging the MZI in a small container, as shown in Fig. B2(a), will also help with thermal and acoustic isolation. One may also need to close the doors to the lab, or wait for the temperature to stabilize after placing the laser and/or MZI in the isolation box.

Appendix B

HIGH CURRENT BATTERY SOURCE

In order to reduce the impact of laser current noise on the phase noise, especially for current biases exceeding 1 A, it was necessary to construct a current supply based on a battery. A very simple high current supply was constructed from a 12 V, 100 A-hr car battery, several high power resistors [Ohmite L100J2R0E Power Resistor distributed by DigiKey], and a high-power rheostat [Ohmite RJS35RE distributed by DigiKey] with a maximum current rating of 1.2 A. A schematic of the current supply constructed to bias the diode laser is shown in Fig. B1. The rheostat could be used to adjust the lower currents continuously. In addition, wire jumpers between the resistors were used for large adjustments for current levels above 1 A. Care needed to be taken not to overheat these high power components that could still get quite hot to the touch. A more optimum design would incorporate heat sinking of the resistors. At the highest currents, around 3.5 A, the rheostat needed to be operated near its lowest resistance value so as not to overheat the few remaining resistive turns. Rheostats with higher current ratings were much more expensive and had coarser adjustment contacts. A photograph of the high power current supply is shown in Figs. B2 (b) and (c).

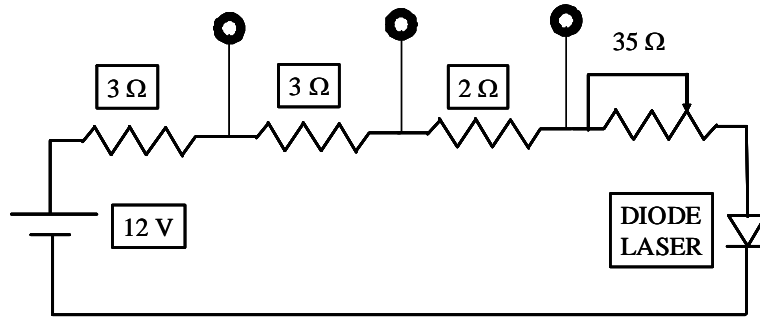


Figure B1. High-current, battery-based, circuit diagram used to bias the SCOWECSL laser. In conjunction with a 12 Volt car battery, high power resistors [Ohmite], with jumpers to short select resistors, and a high-power rheostat [Ohmite] were used to adjust the current bias.

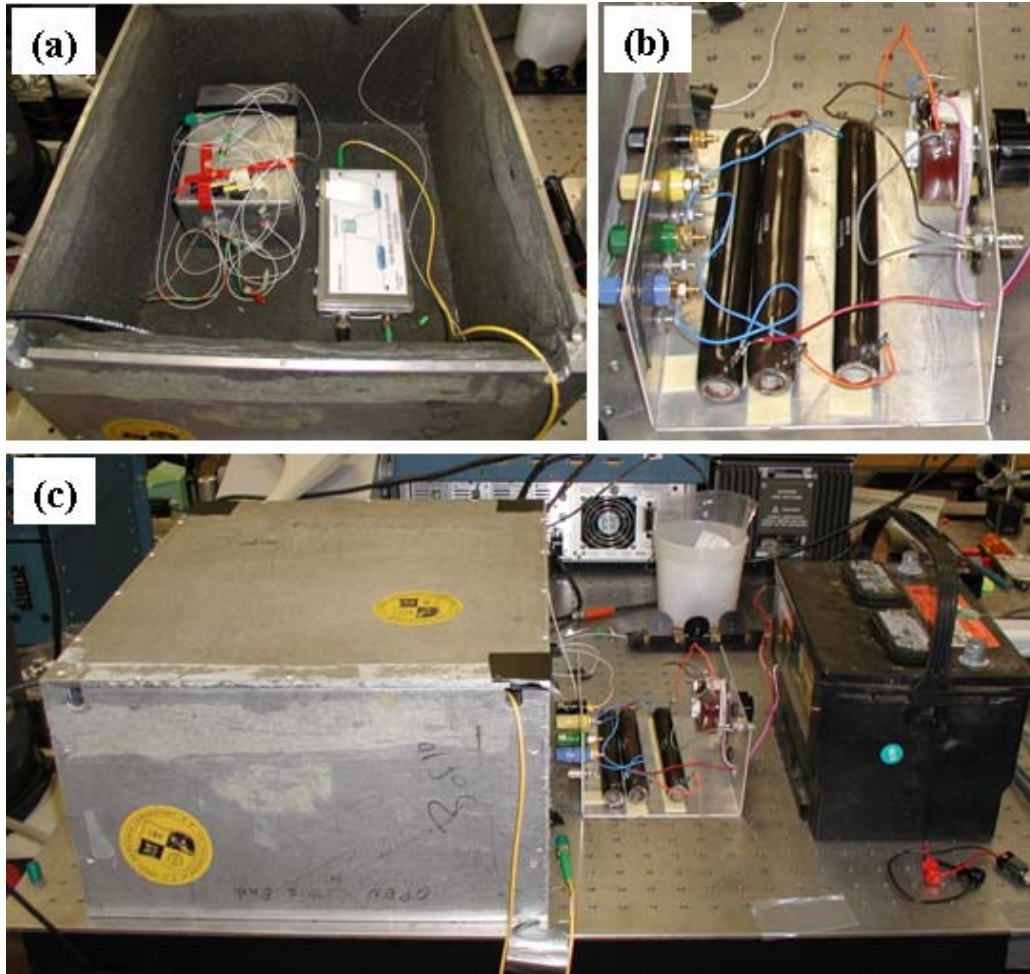


Figure B2. Phase noise measurement set-up. (a). A metal box lined with a lead foam composite [Soundcontrol Mat/Doublemat, one inch thick, lead barrier, United Foam (Formerly E.N. Murray)] with two encased MZIs inside [see for example Optiphase MFI Michelson Fiber Interferometer]. (b) Close-up of the high power circuit depicted schematically in Fig. B1 with 3 cylindrical high-power Ohmite resistors and an Ohmite rheostat for adjusting the current. (c) The same setup as in (a) and (b), but with the lid to the “lead-lined” box in place.

Appendix C

DIRECTIONS FOR FUTURE RESEARCH: REDUCING THE 1/f NOISE

This paper has shown that the phase noise contribution from spontaneous emission can be reduced to the point that only the 1/f noise is observable over a wide frequency range. Likewise, the phase noise of a Nd:YAG is dominated by 1/f noise from 1 Hz to 10 MHz, and is only a factor of 20 smaller than for the SCOWECL. An important research goal is to reduce the 1/f noise of the SCOWECL, by a factor of 20, to achieve the same level of noise performance as the Nd:YAG. If past research on 1/f noise in semiconductor lasers is any indication, a reduction by a factor of 20 in the phase noise for ECSLs is certainly feasible. This is especially true for the prototype SCOWECL used in this work since it was not optimized to reduce the 1/f noise in any way.

Several past research efforts have investigated the origins of the 1/f noise in semiconductor lasers and developed techniques for reducing it. Experimental research on semiconductor lasers has correlated the 1/f noise with fluctuations of the buried heterostructure (BH) leakage current I_{BH} that bypasses the multiple quantum well (MQW) region [9]. Theoretical work by Fukuda [10] has shown that the frequency noise scales with the leakage current, $S_v(f) \sim I_{BH}$, which was consistent with measurements of the residual linewidth floor. Other work seems to reinforce this idea by showing a connection between deviations from ideal diode I-V performance (due to leakage currents) and 1/f noise in buried heterostructure lasers [1, 11]. Therefore, depending on the magnitude of the leakage current of the SCOWECL, a reduction of the 1/f noise by approximately a factor of 3 would not be unreasonable. Previous research has also shown that the excess 1/f *electrical* noise could be reduced considerably through the use of a sulphur passivation process of the cleaved facets where unbonded III-V sites likely act as defect centers [12]. This has not been tried on the SCOWECL, yet might lead to a significant reduction in the 1/f noise. Mode competition noise has also been shown to be a factor, and can certainly be reduced through the design of better, more narrow bandwidth fiber Bragg gratings [24]. To date there has been no systematic study to reduce the 1/f noise by either minimizing leakage currents, performing a sulphur passivation process, or by reducing mode competition noise. Taken together, a reduction of the phase noise by a factor of 10 should be feasible.

Another approach for reducing the 1/f noise is by systematically reducing the linewidth enhancement factor (LEF) α discussed in connection with Eq. (2). The LEF quantifies the strong coupling between intensity fluctuations and frequency fluctuations. The LEF is much larger in semiconductor lasers, relative to solid state lasers, and is the leading cause for the enhancement of their phase noise [14]. Mathematically α is given by the following expression:

$$\alpha = \frac{4\pi}{\lambda} \frac{dn_r / dN}{dg / dN} \quad (C.1)$$

where n_r is the real part of the refractive index, N is the carrier concentration, and dg/dN is the differential gain. There are many design approaches that can be taken to systematically reduce the LEF. This was shown to be possible in ECSLs through the use of detuned loading and blue detuning [13, 14, 17, 25]. Reducing α should also reduce the 1/f noise, though this has not been proven explicitly. Reducing α has been shown to reduce the instantaneous linewidth by a factor of 7 [26]. Recent work [1] has also shown a factor of ten difference in the magnitude of the 1/f noise between ECSLs designed for digital applications as compared to analog applications, where linearity and chirp parameters have been optimized. Further reductions are certainly possible as has been shown recently for a new class of ECSLs based on planar Bragg gratings on silica-on-silicon planar lightwave circuits [2, 7]. Taken together, it should be quite feasible to achieve the same low level of phase noise in semiconductor lasers as in more expensive solid state lasers with continued design and fabrication improvements.

REFERENCES

- [1] R. E. Bartolo and V. Kupershmidt, "Achieving narrow linewidth, low phase noise external cavity semiconductor lasers through the reduction of $1/f$ noise," *Proc. of SPIE*, vol. 6133, pp. 1-8, 2006.
- [2] R. Bartolo, Tveten, A., Kirkendall, C.K., "The quest for inexpensive, compact, low phase noise laser sources for fiber optic sensing applications," *Proc. of SPIE*, vol. 7503, p. 750370, 2009.
- [3] C. K. Kirkendall, A. D. Kersey, A. Dandridge, M. J. Marrone, and A. R. Davis, "Sensitivity Limitations Due to Aliased High Frequency Phase Noise in High Channel-Count TDM Interferometric Arrays," in *Optical Fiber Sensors*, 1996, pp. Fr1-4.
- [4] P. W. Juodawlkis, W. Loh, F. J. O'Donnell, M. A. Brattain, and J. J. Plant, "High-Power, Ultralow-Noise Semiconductor External Cavity Lasers Based on Low-Confinement Optical Waveguide Gain Media," *Proceedings of the SPIE - The International Society for Optical Engineering*, vol. 7616, p. 76160X (9 pp.), 2010.
- [5] P. W. Juodawlkis, W. Loh, F. J. O'Donnell, M. A. Brattain, and J. J. Plant, "Ultralow-Noise Packaged 1.55- μ m Semiconductor External-Cavity Laser with 0.37-W Output Power," *2009 Conference on Lasers and Electro-Optics and Quantum Electronics and Laser Science Conference (Cleo/QELS 2009)*, Vols 1-5, pp. 796-797, 2009.
- [6] P. W. Juodawlkis, J. J. Plant, R. K. Huang, L. J. Missaggia, and J. P. Donnelly, "High-power 1.5- μ m InGaAsP-InP slab-coupled optical waveguide amplifier," *Ieee Photonics Technology Letters*, vol. 17, pp. 279-281, Feb 2005.
- [7] L. Stolpner, S. Lee, S. Li, A. Mehnert, P. Mols, S. Siala, and J. Bush, "Low noise planar external cavity laser for interferometric fiber optic sensors - art. no. 700457," in *19th International Conference on Optical Fibre Sensors*, Perth, AUSTRALIA, 2008, pp. 457-457.
- [8] K. Kikuchi, "Effect of $1/F$ -Type Fm Noise on Semiconductor-Laser Linewidth Residual in High-Power Limit," *IEEE Journal of Quantum Electronics*, vol. 25, pp. 684-688, Apr 1989.
- [9] M. Fukuda, T. Hirono, T. Kurosaki, and F. Kano, " $1/F$ Noise Behavior in Semiconductor-Laser Degradation," *IEEE Photonics Technology Letters*, vol. 5, pp. 1165-1167, Oct 1993.
- [10] M. Fukuda, T. Hirono, T. Kurosaki, and F. Kano, "Correlation between $1/F$ Noise and Semiconductor-Laser Degradation," *Quality and Reliability Engineering International*, vol. 10, pp. 351-353, Jul-Aug 1994.
- [11] I. A. Garmash, V. N. Morozov, A. T. Semenov, M. A. Sumarov, and V. R. Shidlovskii, "Leakage Currents and $1/f$ Noise in Buried in GaAs/InP Heterostructure Lasers," *Kvantovaya Elektronika*, vol. 17, pp. 964-968, Aug 1990.
- [12] R. Hakimi and M. C. Amann, "Reduction of $1/f$ carrier noise in InGaAsP/InP heterostructures by sulphur passivation of facets," *Semiconductor Science and Technology*, vol. 12, pp. 778-780, Jul 1997.
- [13] R. F. Kazarinov and C. H. Henry, "The Relation of Line Narrowing and Chirp Reduction Resulting from the Coupling of a Semiconductor-Laser to a Passive Resonator," *IEEE Journal of Quantum Electronics*, vol. 23, pp. 1401-1409, Sep 1987.
- [14] C. H. Henry, "Phase Noise in Semiconductor-Lasers," *Journal of Lightwave Technology*, vol. 4, pp. 298-311, Mar 1986.
- [15] R. F. Kazarinov, C. H. Henry, and N. A. Olsson, "Narrow-Band Resonant Optical Reflectors and Resonant Optical Transformers for Laser Stabilization and Wavelength Division Multiplexing," *Ieee Journal of Quantum Electronics*, vol. 23, pp. 1419-1425, Sep 1987.
- [16] C. H. Henry, "Theory of Spontaneous Emission Noise in Open Resonators and Its Application to Lasers and Optical Amplifiers," *Journal of Lightwave Technology*, vol. 4, pp. 288-297, Mar 1986.
- [17] C. H. Henry, "Line Broadening of Semiconductor Lasers," in *Coherence, Amplification, and Quantum Effects in Semiconductor Lasers*, Y. Yamamoto, Ed. New York: A Wiley-Interscience Publication, 1991, pp. 5-76.

- [18] R. W. Tkach and A. R. Chraplyvy, "Phase Noise and Linewidth in an InGaAsP DFB Laser," *Journal of Lightwave Technology*, vol. 4, pp. 1711-1716, Nov 1986.
- [19] L. B. Mercer, "1/F FREQUENCY NOISE EFFECTS ON SELF-HETERODYNE LINEWIDTH MEASUREMENTS," *Journal of Lightwave Technology*, vol. 9, pp. 485-493, Apr 1991.
- [20] L. A. Coldren and S. W. Corzine, *Diode Lasers and Photonic Integrated Circuits*: John Wiley & Sons, Inc.
- [21] A. Dandridge, "Fiber Optic Sensors Based on the Mach-Zehnder and Michelson Interferometers," in *Fiber Optic Sensors: An Introduction for Engineers and Scientists*, E. Udd, Ed.: John Wiley & Sons, Inc., 1991, pp. 271-323.
- [22] A. D. Kersey, Williams K.J., Dandridge, A., Weller, J.F., "Characterization of a Diode Laser-Pumped Nd:YAG Ring Laser for Fiber Sensor Applications," in *Optical Fiber Sensors: Proceedings of the 6th International Conference, OFS 89*, 1989, pp. 172-178.
- [23] C. K. Kirkendall and A. Dandridge, "Overview of high performance fibre-optic sensing," *Journal of Physics D-Applied Physics*, vol. 37, pp. R197-R216, 2004.
- [24] M. Ohtsu, Y. Teramachi, Y. Otsuka, and A. Osaki, "ANALYSES OF MODE-HOPPING PHENOMENA IN AN ALGAAS LASER," *IEEE Journal of Quantum Electronics*, vol. 22, pp. 535-543, Apr 1986.
- [25] C. H. Henry, "Theory of the Linewidth of Semiconductor-Lasers," *IEEE Journal of Quantum Electronics*, vol. 18, pp. 259-264, 1982.
- [26] J. M. Verdiell, U. Koren, and T. L. Koch, "LINEWIDTH AND ALPHA-FACTOR OF DETUNED-LOADED DBR LASERS," *IEEE Photonics Technology Letters*, vol. 4, pp. 302-305, Apr 1992.